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Capacity Statement for Railways

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1 Abstract

The subject “Railway capacity” is a combination of the capacity consumption and how the capacity is utilized. The capacity utilization of railways can be divided into 4 core elements: The number of trains; the average speed; the heterogeneity of the operation; and the stability.

This article describes how the capacity consumption for railways can be worked out and analytical measurements of how the capacity is utilized. Furthermore, the article describes how it is possible to state and visualize railway capacity.

Having unused railway capacity is not always equal to be able to operate more trains. This is due to network effects in the railway system and due to the fact that more trains results in lower punctuality.

Keywords: Railway capacity, Capacity, UIC 406, Capacity consumption, Capacity utilization

2 Introduction

The railway sector has in recent years been divided into rail authorities, infrastructure managers and operators. Furthermore, more construction companies and consultants have started working with railways. The many new companies result in a need for consensus of how to express and communicate core elements such as railway capacity.

As a consequence of no consensus on railway capacity the International Union of Railways (UIC) published a leaflet – the UIC 406 capacity leaflet – describing railway capacity in the year 2004. The UIC 406 capacity method defines railway capacity as “the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively...” [25].

Since the publication of the UIC 406 capacity leaflet many organizations inside the railway sector have been working on how to expound the capacity leaflet to calculate the capacity consumption. This work has been published in a number of publications, e.g. [1], [2], [8], [9], [10], [11] and [23]. However, only little work has been done on how to state and present the railway capacity – e.g. [15] and [23]. Therefore, this article will present how to state and present railway capacity in a straightforward way according to the internationally accepted UIC 406 capacity method.

First, the article gives a short introduction on how to calculate capacity consumption for railway lines in section 3. This is followed by a description of how to examine the utilization of railway capacity in section 4. Based on the calculation of capacity consumption and the examination of capacity utilization, it is described how railway capacity can be stated in section 5. This is followed by a discussion in section 6 and concluding remarks in section 7.

3 Calculating the capacity consumption

To measure railway capacity consumption it is necessary to know the timetable graphs for the railway line(s) examined. By using the timetables graphs for the given infrastructure the dynamics of rolling stock is implicitly included as the rolling stock is determining the size of the blocking stairs. The capacity consumption of the railway infrastructure is then measured by compressing the timetable graphs so that the buffer times are equal to zero, cf. figure 1. This compression considers the minimum headway times, which depends on the interlocking system and train characteristics [21].

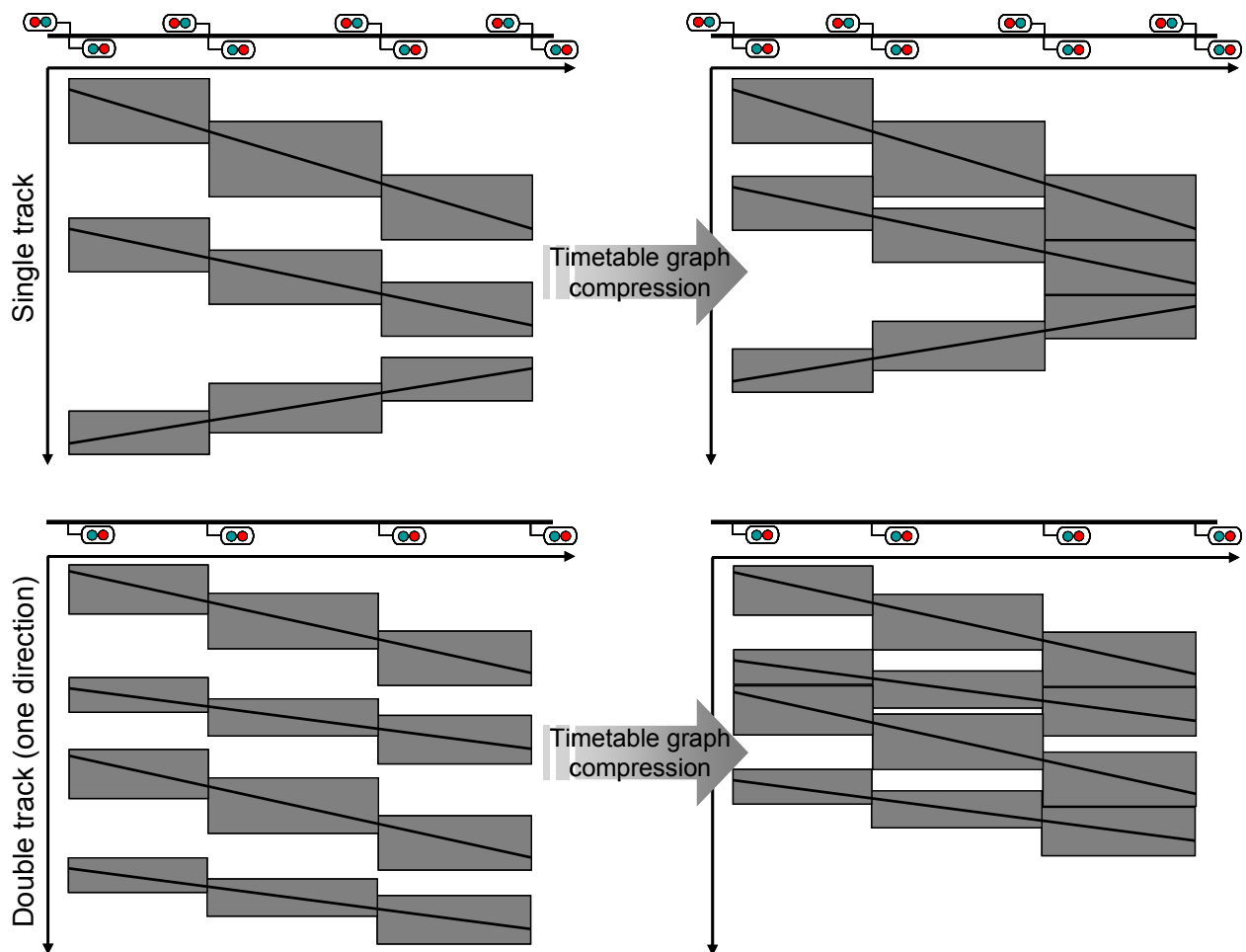


Figure 1: Compression of timetable graph according to the UIC406 capacity method. Partly based on [8]

As it is difficult or even impossible to compress the timetable graphs for an entire complex railway network, it is necessary to divide the network into smaller line sections which easily

can be handled by the UIC 406 capacity method. Railway lines are divided into smaller line sections at junctions, overtaking stations, line end stations, transition between double track and single track (or any other number of tracks) and at crossing stations, cf. figure 2.

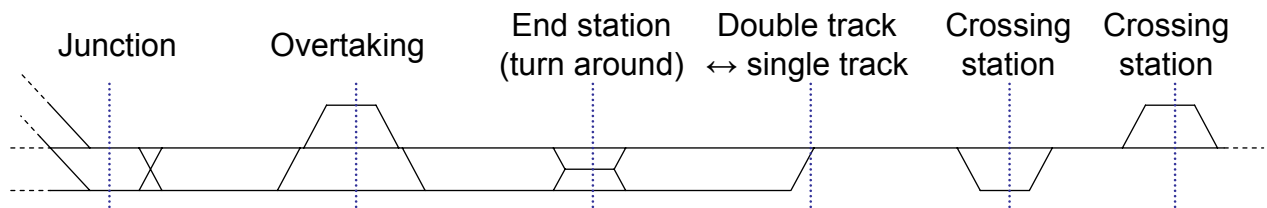


Figure 2: Division of railway line into line sections [10][11].

The capacity consumption depends on both the infrastructure and the timetable why it is necessary to include both in the evaluation. Therefore, the first step of evaluating the railway capacity is to build up the infrastructure and create/reproduce the timetable. To evaluate the railway capacity according to the UIC 406 method, the railway network has to be divided into line sections. For each line section the timetable has to be compressed so that the minimum headway time between the trains is achieved. When the timetable has been compressed it is possible to work out the capacity consumption of the timetable by comparing the cycle times (the compression ratio). The workflow of the capacity evaluation can be seen in figure 3.

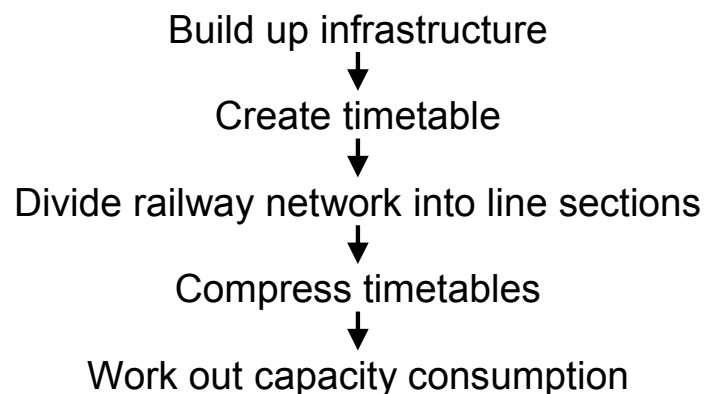


Figure 3: General workflow of the UIC 406 method [10]

In practice railway capacity for a given line section can be worked out manually (as shown in figure 3) in any timetabling system with conflict detection – e.g. RailSys and the Danish STRAX system (see e.g. [6] and [22]). Some timetabling systems (e.g. RailSys) have functions which can assist the user in working out the capacity consumption according to the UIC 406 capacity method [19]. This calculation of capacity consumption can then be used to create maps to illustrate the state of the capacity, for example, where there is a lack of capacity, cf. figure 4.

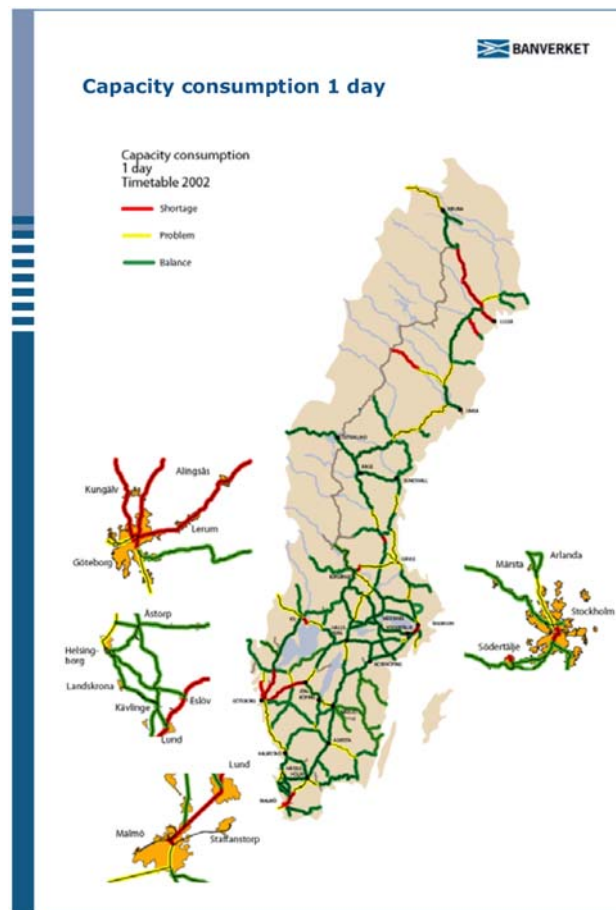


Figure 4: Capacity consumption in Sweden [24].

It is not only the present – or previous – capacity consumption that can be presented on maps. The Austrian railways (ÖBB) also present future scenarios based on traffic forecasts and a combination of macro and micro simulation – the so-called meso simulation [21], cf. figure 5.

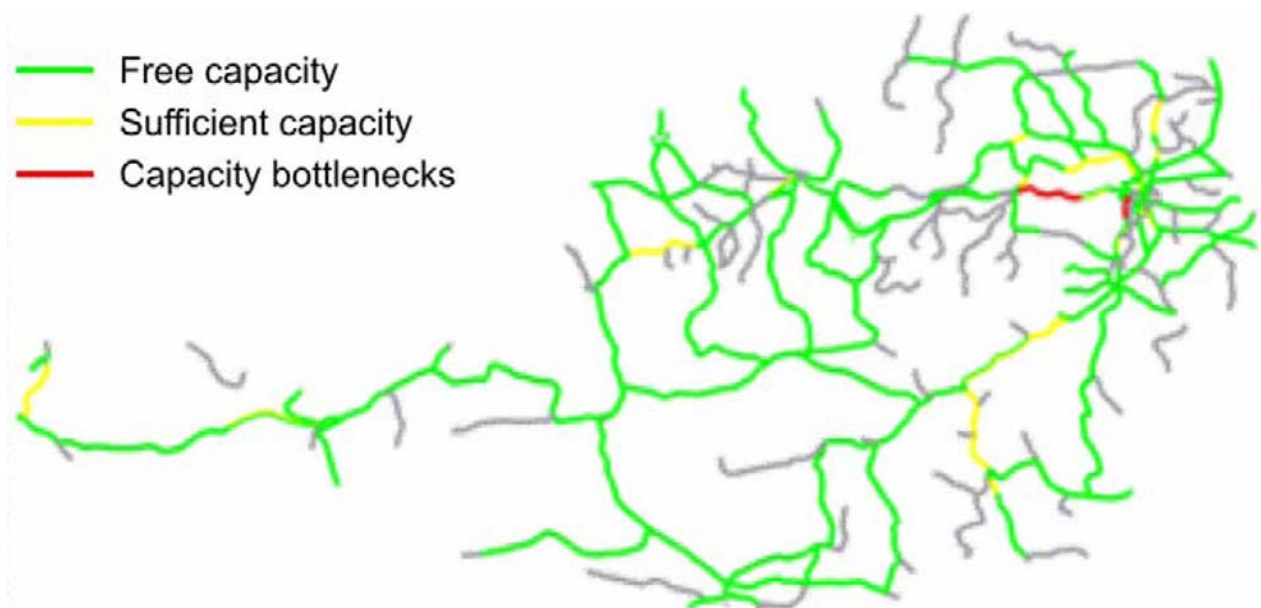


Figure 5: Capacity utilization for a fictitious scenario on the Austrian railway network [21].

3.1 Intervals of capacity statement

The previous section showed that it is relatively easy to visualize the capacity consumption for railway lines (or line sections) on maps. However, when visualising the capacity consumption one question remains – which level of capacity consumption indicates lack of capacity?

The level of capacity consumption indicating lack of capacity needs to ensure a certain level of buffer time in the timetables to reduce the risk of secondary delays – and thereby ensure a certain punctuality level. UIC has suggested levels for the maximum capacity consumptions on railway lines shown in table 1.

Table 1: UIC intervals for maximum capacity consumption [25].

Type of line	Peak hour	Daily period	Comment
Dedicated suburban passenger traffic	85%	70%	The possibility to cancel some services allows for high levels of capacity utilization.
Dedicated high-speed lines	75%	60%	
Mixed-traffic lines	75%	60%	Can be higher when number of trains is low (lower than 5 per hour) with strong heterogeneity.

The UIC suggests different values for maximum capacity consumptions depending on the type of railway line and time period examined. The higher suggested maximum capacity consumption in the peak hour (compared to the entire day) can be explained by the acceptance of having less possibility to recover from delays in shorter periods during the day. The difference in suggested maximum capacity consumption for different types of lines can be explained by the risk of secondary delays. A mixed-traffic line with a heterogeneous timetable has a higher risk of secondary delays than a homogeneous line operation because faster trains catch up with slower trains. An unplanned stop or a speed reduction of a high-speed line often leads to more delays than for railway lines with lower speed. Suburban railway lines (normally) have homogeneous operation with a high frequency. It is therefore relatively easy to recover from incidents or more delays by cancelling some of the trains, which is why the UIC suggests higher maximum capacity consumption.

To visualize capacity consumptions on simple maps it is necessary to define intervals for the capacity consumption. These intervals can be either values or descriptions such as shortage/problem, balance and sufficient capacity. Using descriptions for the defined intervals makes the maps more understandable for non-technicians but to compare different maps, the

maps must have the same interval definitions. In Sweden it has been decided to use the definition in table 2 for the capacity consumption¹:

Table 2: Swedish intervals for capacity consumption with no quality factor or other supplements [1][2][24].

	Max 2 hours	All day
Shortage	81 – 100%	81 – 100%
Problem	61 – 80%	61 – 80%
Balance	Up to 60%	Up to 60 %

The intervals in table 2 are not identical to the values suggested by UIC in the capacity leaflet [25] (cf. table 1). The Swedish intervals are identical for all types and lines and the all-day period and the two-hour period. Not surprisingly it has been shown that there are more railway lines with capacity shortage/problems in the peak hours [24].

It is difficult – if not impossible – to have intervals that are meaningful in all situations. E.g. if the railway line in figure 6 has a capacity consumption of 48% if only the blue (unbroken) trains are unbroken then the capacity consumption would be 96% if also the red (dotted) trains are operated. With a capacity consumption of 48% it would normally be possible to operate an extra train why it might be stated that there are no capacity problems or shortage. However, if the blue (unbroken) trains are operated in an hourly pattern it is not possible to operate the red (broken) trains in an hourly pattern too as the operation would become unstable. Therefore, the operation in an hourly pattern is actually suffering from capacity problems – at least if desirable to operate more trains in hourly patterns.

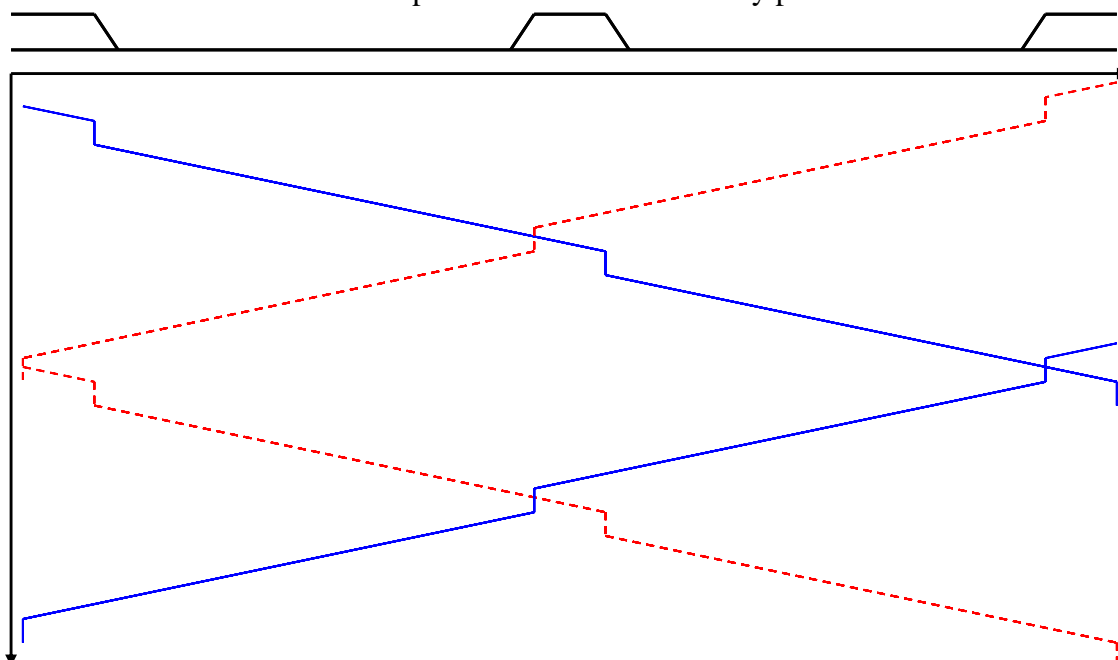


Figure 6: Trains operated in hourly pattern – each pattern has a capacity consumption of 48%².

¹ Without any quality factors or other supplements.

² See [8] for a more detailed explanation of how to work out the capacity consumption for single track lines.

That different levels of capacity consumptions are used for identifying the maximum possible capacity consumption is because extra train paths can be added to the timetable by accepting lower punctuality. In other words, the maximum capacity consumption depends on the stability request of the timetable [15]. It is therefore possible to use simulation tools such as OpenTrack and RailSys to estimate the maximum capacity consumption accepted. However, it is not possible to decide the exact/final level for maximum capacity consumption before the quality factor has been decided.

3.2 Quality factor

Quality factors can be used to ensure a high quality operation. However, using the quality factor means that the interval of identifying the critical level of capacity is changed. Therefore, the decided intervals of capacity statement and the quality factor are dependent. The Austrian railways (ÖBB) has according to [15] chosen to use simulation of the railway operation to identify the needed quality factor³ to achieve a satisfactory level of punctuality.

The quality factor can be estimated as a percentage of the capacity consumption – e.g. 20%. When defining the quality factor it is possible to calculate the unused capacity, cf. table 3. Normally the unused capacity can be considered as used for punctuality and/or network effects where railway capacity is “lost” because of restrictions in the network outside the analysis area. However, by including the quality factor these parameters are indirectly included in the statement. If construction work is planned (for a longer period) it might be necessary to include a supplement for maintenance when calculating the capacity consumption, cf. scenario B in table 3.

Table 3: Calculation of capacity consumption for a 2 hour period.

Scenario	A	B	C
Infrastructure occupation [min]	95	80	105
Supplement for maintenance [min]	0	10	0
Quality factor [%]	20	20	20
Quality factor [min]	19	16	21
Capacity consumption [min]	114	106	126
Capacity consumption [%]	95	88	105
Not used capacity [min]	6	14	–
Not used capacity [%]	5	12	–

In cases where the unused capacity stated in column A and B in table 3 can be used to operate more trains by adding additional train paths (some of) the unused capacity can be transferred

³ The quality factor describes the buffer times in the timetable compression. See [8] and [25] for more details about the quality factor.

to usable capacity. However, it might not be possible to operate all kinds of trains and if the buffer times are too small to add an extra train path the unused capacity can be considered as lost capacity (with the given timetable).

The paradox that the capacity consumption exceeds 100% can occur when using the quality factor in capacity statements, cf. column C in table 3. However, capacity consumptions above 100% “just” state that it is not possible to operate the traffic with a satisfactory or decided stability/punctuality.

Using the quality factor as a percentage of the capacity infrastructure occupation time leads to another paradox as trains that occupy the infrastructure for the longest time get the highest quality supplement, e.g. if the slow (blue unbroken) trains in figure 7 have a infrastructure occupation time of 5 minutes each and the fast (red broken) train has an infrastructure occupation time of 2½ minutes, the quality supplement will be 2½ minutes (20% quality factor assumed). The 2½ minutes of quality supplement will be distributed so that the slow trains have 1 minute each and the fast train only ½ minute. However, it is the fast train that has the highest risk of delays and will be affected the most from secondary delays. It can therefore be discussed if the distribution of quality supplement is fair.

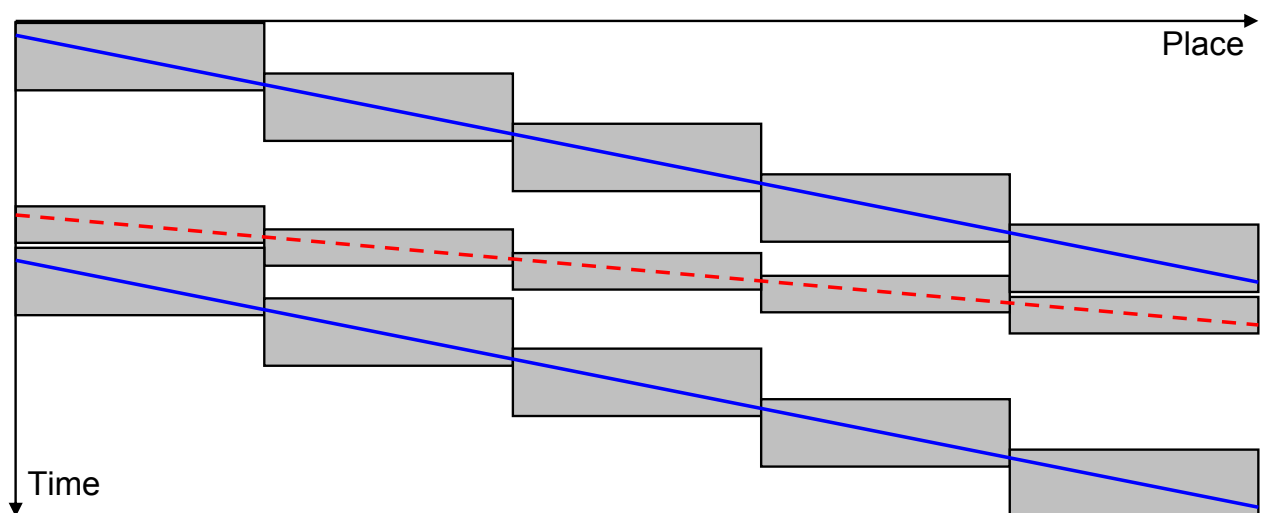


Figure 7: Infrastructure occupation.

To have a fairer distribution of the quality supplements the quality factor could be allocated to each train as either an individual percentage or a fixed (time) value for each train type. Using fixed (time) intervals it is also ensured that line sections with long block lengths do not get higher quality supplements per train than line sections with shorter block lengths (or moving block).

Using small fixed (time) supplements would not help on the paradox in figure 6 (see section 3.1) – there would be capacity problems although the capacity consumption is below 50%. However, using a quality factor as a percentage of the capacity consumption would be more

effective as the occupation time is higher. Therefore, I suggest that fixed (time) intervals are used as quality factors for double track railway lines and quality factors as a percentage of the capacity consumption is used for single track railway lines.

4 Capacity utilization

Figure 4 and figure 5 in section 3 show the capacity consumption of railway lines in Sweden and Austria but the figures do not show how the capacity is utilized. Not showing how the capacity is utilized can result in the paradox that a railway line that operates as many trains as possible has a lower capacity consumption than a railway line which operates much fewer trains but in a heterogeneous way.

To avoid – or at least to explain – the paradox that a timetable with many trains gives lower capacity consumption than a timetable with fewer trains it is necessary to incorporate how the capacity is utilized. Therefore, railway capacity cannot be explained by either the capacity consumption or the capacity utilization – it is necessary to describe both.

The UIC capacity leaflet defines the parameters of capacity consumption in the “balance of capacity” (number of trains, average speed, heterogeneity and stability). The UIC capacity leaflet also suggests a methodology to determine the capacity consumption using compressed timetable graphs as described in section 3. However, to describe both the capacity consumption and the capacity utilization it is necessary to add an extra dimension – the capacity consumption – to the balance of capacity. This gives the “capacity pyramid” cf. figure 8.

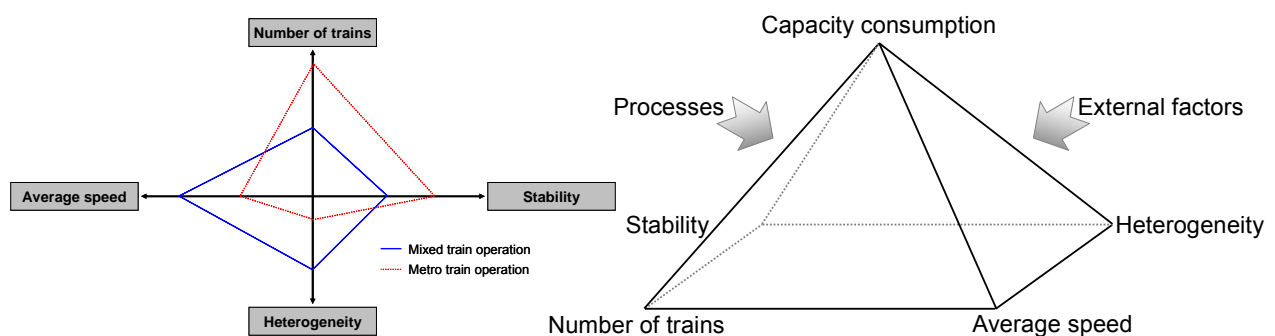


Figure 8: Railway capacity – balance of capacity to the left and the capacity pyramid to the right [9].

The following sections give a short presentation of analytical measurements for the “balance of capacity”⁴: Number of trains, section 4.1; Heterogeneity, section 4.2; Average speed, section 4.3; and stability, section 4.4.

⁴ For a more detailed description please refer to [9].

4.1 Number of trains

When operating many trains per hour it is not always possible to combine trains stopping at all stations and faster through going trains. This is due to the fact that the faster trains will catch up with the slower trains which cause conflicts, cf. figure 9. Hence fast trains catch up with slower trains all trains will have the same stopping pattern when close to the maximum capacity and/or it is necessary to bundle trains with the same travel speed – the timetable will be (almost) homogeneous. Bundling of trains and slowing down the fastest trains result in a reduced service for the passengers.

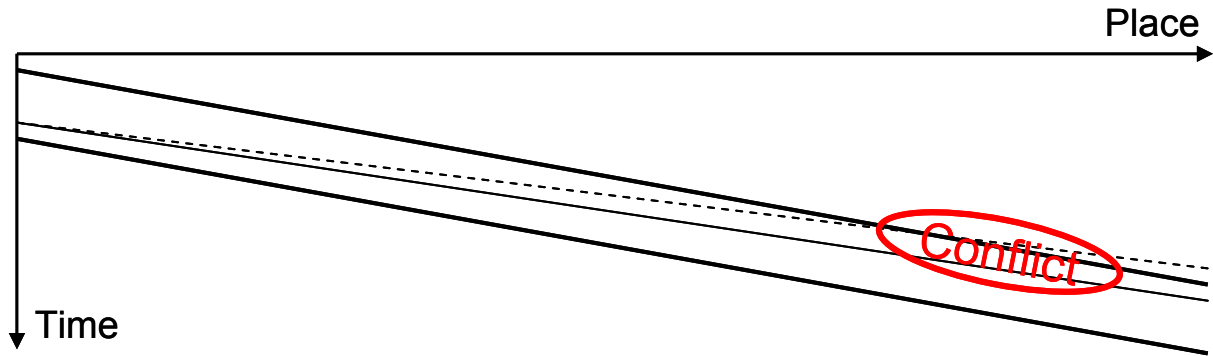


Figure 9: Fast train catching up with a slower train [3] & [20].

[9] suggests that the measurement for the number of trains is simply the number of trains operated on a line section.

4.2 Heterogeneity

A timetable is heterogeneous (or not homogeneous) when a train catches up with another train. To describe the heterogeneity of timetables it is necessary to take both the variation in speed (and thereby stop pattern) and the variation in headway times into account [16]. By examining the headway times at one station it is possible to examine the variation in headway times but not the variation in speed and stop pattern. However by examining the headways in both ends of a line section it is possible to examine the variation in headway times in both ends of the line section but it is also possible to examine the variation in speed.

The heterogeneity can be calculated by taking both the variation in headway times and speed into account by taking the ratio between the headway time at the departure station ($h_{t,i}^D$) and the following headway time ($h_{t,i+1}^D$). The same ratio is taken at the arrival station using $h_{t,i}^A$ and $h_{t,i+1}^A$ and multiply the ratio with the ratio at the departure station. To make the heterogeneity measure independent from the number of trains in the time period examined, the ratios are divided by the number of headways minus 1 (h_{N-1}) examined. Based on these assumptions [9] suggests using the following measurement for the heterogeneity:

$$\text{Heterogeneity} = 1 - \frac{\sum \left(\min \left(\frac{h_{t,i}^D}{h_{t,i+1}^D}; \frac{h_{t,i+1}^D}{h_{t,i}^D} \right) \cdot \min \left(\frac{h_{t,i}^A}{h_{t,i+1}^A}; \frac{h_{t,i+1}^A}{h_{t,i}^A} \right) \right)}{h_{N-1}}$$

4.3 Average speed

A train consumes a different amount of capacity at different speeds. When a train stands still, the train consumes all the capacity since it occupies the block section for an infinite amount of time. When the train speeds up the train occupies the block section for shorter time whereas more trains can pass the same block section – more capacity is gained. However, when increasing the speed also the braking distance is increased which means that the headway distance – and headway time – is increased whereas capacity is lost, cf. figure 10.

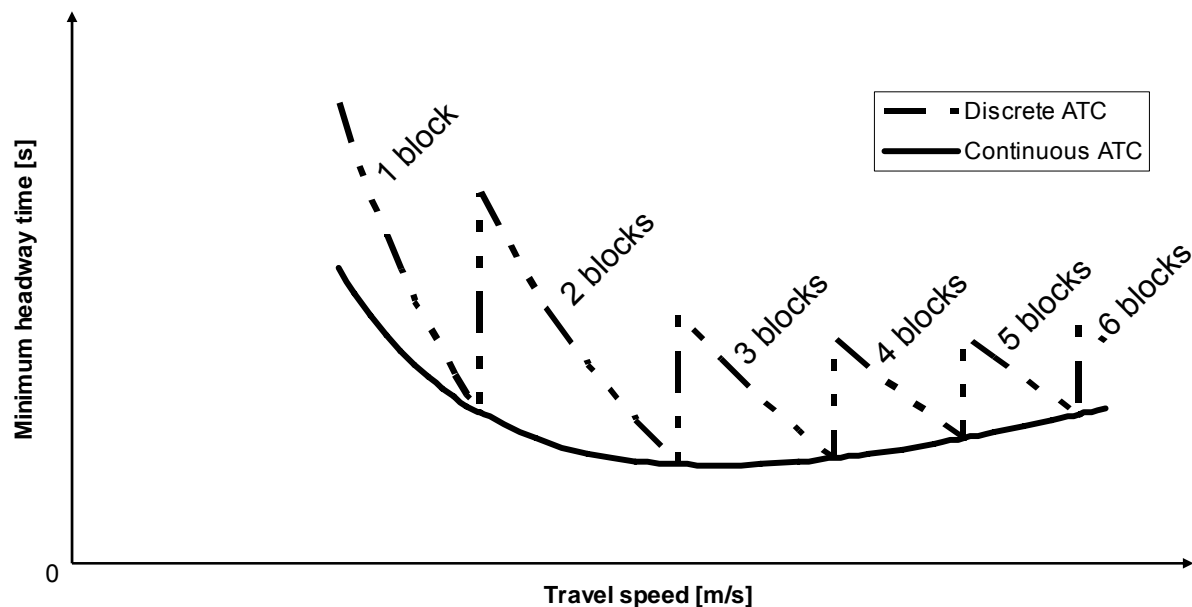


Figure 10: Minimum headway time (for traditional block systems) according to the speed of the train [13].

When a train speed (v_i) is different from the optimal speed of the train (v_{opt}) capacity is lost. However, it is difficult to describe how much capacity is lost in an easy way why a more easy approach describing the average deviation from the optimal speed (V) is suggested by [9]:

$$V = \frac{|v_{opt} - v_i|}{N}$$

4.4 Stability

The stability of railway systems is difficult to work out as such but the stability depends on the complexity of the operation. The complexity of the operation depends on the heterogeneity and conflicts between train routes. As the heterogeneity has been dealt with in section 4.2 it would be double counting to include it in the stability too, why it is only the conflicts between train routes that are included in the stability.

The conflicts between train routes – the so-called conflict rates – can be analyzed analytically according to the methodology described in [17]⁵. The result of the complexity is always

⁵ The calculation of the conflict rates is too extensive to present in this article. Examples of calculation of conflict rates can be found in [9].

between 0 and 1 where high complexity value indicates a low stability and vice versa. According to [9] it is suggested to calculate the stability as:

$$\text{Stability} \approx 1 - \text{complexity}$$

5 Capacity statement

It is impossible to visualize all the elements from the capacity pyramid on a map at the same time unless a weighted average is calculated. However, the elements in the capacity pyramid can be weighted differently in different situations, which is why it is difficult to find the right weights for the weighted average. Instead the most interesting element from the capacity pyramid (often the capacity consumption) can be visualized in a GIS based system with the possibility to click on the line sections to examine all the elements of the line section as shown in figure 11.

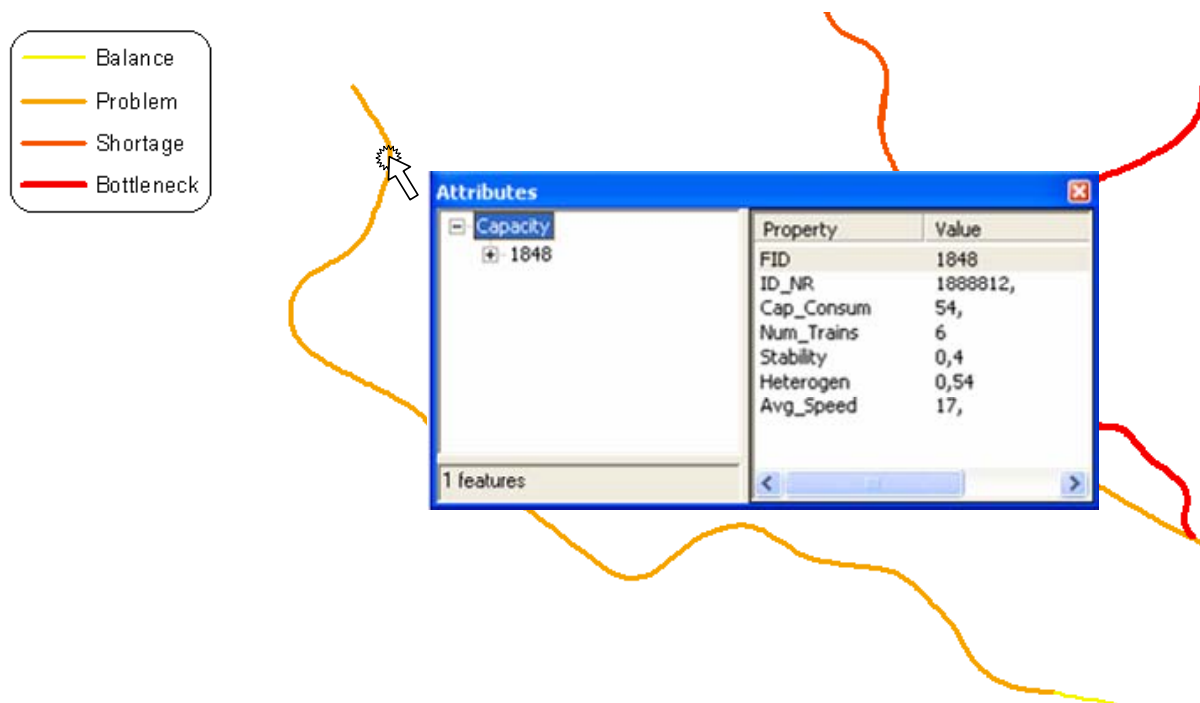


Figure 11: Visualization of railway capacity in a fictitious example.

By describing the railway capacity analytically it is possible to get more information than just the capacity consumption. It is possible to describe why a certain line section has high capacity consumption – e.g. due to high heterogeneity or many trains. In this way the analyst/planner can communicate the reason for the high capacity consumption and how it is possible to e.g. operate more trains. However, if a planner knows the capacity consumption, the heterogeneity, the average speed, number of trains and complexity of the stations (stability) it might (based on historical data) be possible to predict the future punctuality.

5.1 From maximum capacity to available capacity

When describing railway capacity analytically one has to be aware that the capacity described is for the ideal situation – the maximum capacity. In everyday operation external factors and processes affect the railway capacity (cf. figure 8) which reduces the amount of capacity that is actually available.

The fundamental capacity is (normally) smaller than the maximum capacity. The fundamental capacity allows for restrictions in the reliability of the infrastructure, rolling stock and crew. These restrictions are permanent and can be evaluated. The restrictions can either occur randomly or as planned and recurrent. Therefore, the fundamental capacity can adopt different values depending on the probability of failures. However, there is no method which can be used to calculate it explicitly based on the maximum capacity [12].

Due to the lack of explicitly calculation rules for the fundamental capacity the fundamental capacity will often be assessed as a percentage of the theoretical capacity. According to the UIC 406 capacity leaflet this percentage is between 60% and 85% of the maximum capacity (cf. table 1) depending on the time of the day and the type of railway line [25]. When conducting capacity analysis according to the UIC 406 methodology the quality factor can reflect the percentage of the theoretical capacity – this is the basis of the methodology used by the Austrian Railways as described above [21].

Although the maximum capacity is reduced to the fundamental capacity, lack of capacity can occur – one could say the available capacity is less than the fundamental capacity. This is the case if there is a prolonged shortage on facilities, rolling stock and/or crew but also in case of accidents or weather conditions. The reduction of railway capacity is shown in figure 12.

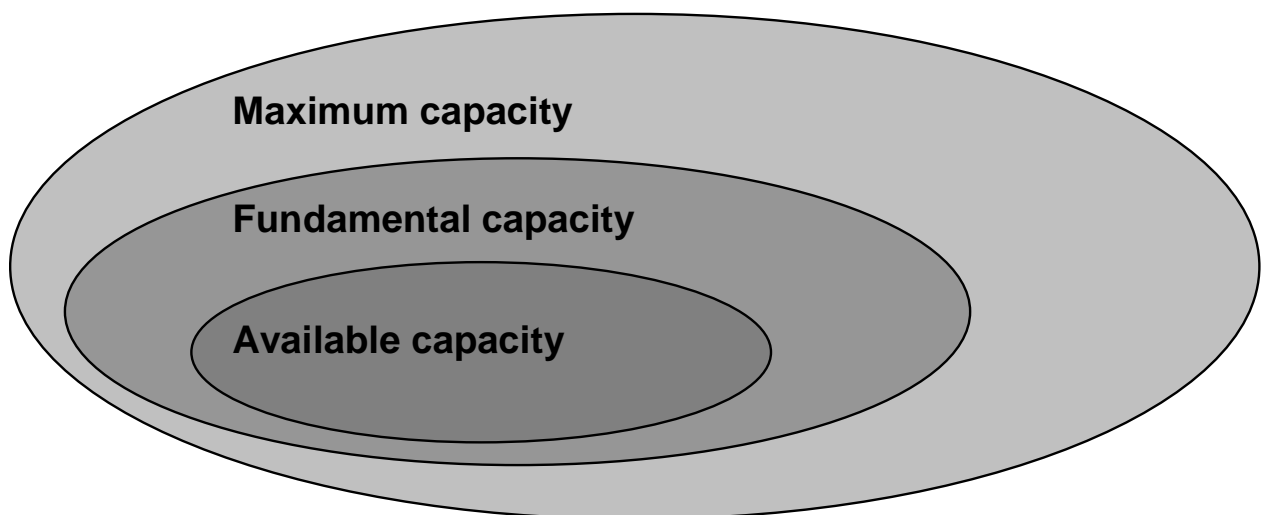


Figure 12: Reduction of railway capacity.

As there are different levels of railway capacity as illustrated in figure 12 one should aim at stating the most realistic capacity – the fundamental capacity. Both Sweden and Austria state

the fundamental capacity but in different ways. The Swedish infrastructure manager illustrates the maximum capacity but with lower intervals equalling the fundamental capacity while Railnet Austria calculates the fundamental capacity using the quality factor in the UIC 406 capacity method.

5.2 Variation in railway capacity

The consumption and utilization of railway capacity varies over the day. Normally, the capacity consumption (for passenger trains) is higher in the rush hours. The capacity consumption can be so high that it is necessary to homogenize the timetable by slowing down the fastest trains and/or not operating freight trains in the rush hours.

Due to the variation in the consumption and utilization of railway capacity the capacity statement should be carried out for different time periods during the day. This gives the planners and analysts the opportunity to identify capacity problems which are not observed if only longer time periods are examined. However, dividing the day into many short time periods does not necessarily result in additional information and if the day is divided into too many periods it might even result in confusing results.

To have useful information about the railway capacity this article recommends that the railway capacity is always stated for the entire day and for the busiest time period during the day. For more detailed analysis the railway capacity can be stated for more time periods during the day.

5.3 Development in railway capacity

To make statements of the capacity utilization it is therefore necessary to consider how the railway network is divided into line sections when presenting maps of the capacity consumption. To have uniform and comparable maps of the capacity consumption it is important to use the same line sections each year. When producing comparable maps of the capacity consumption it can therefore be necessary to “ignore” the UIC 406 guidelines to divide line sections when a crossing, an overtaking or a turnaround takes place.

Although the railway network has been divided carefully into line sections it might be necessary to change the line sections. However, when changing the line sections it is not possible to see the trend of the capacity consumption. Therefore, it is necessary to have an overlap statement between the different line sections as seen in table 4.

Table 4: Change in line sections and capacity consumption [8][10].

	2000	2001	2002	2003
New	n/a	58%	60%	60%
Old	60%	62%	64%	n/a

Examining table 4 it can be seen that the capacity consumption has increased by 4% from year 2000 to 2003. However, if there had not been an overlap statement between the different line sections it would seem that the capacity consumption was the same in year 2000 and 2003 (60%) and a little lower in year 2001 (58%).

Similar to keeping track of the development in capacity consumption it is also important to keep track of the development in the capacity utilization. The changes in the capacity utilization can be registered in the same way as for the capacity consumption. It means that the number of trains, the average speed, the heterogeneity and the stability should be registered each year and have an overlap statement between the different line sections.

6 Discussion

Sometimes it is wanted to use idle capacity to operate more trains. However, it is not always possible to operate more trains as it would result in reduced punctuality, cf. figure 13.

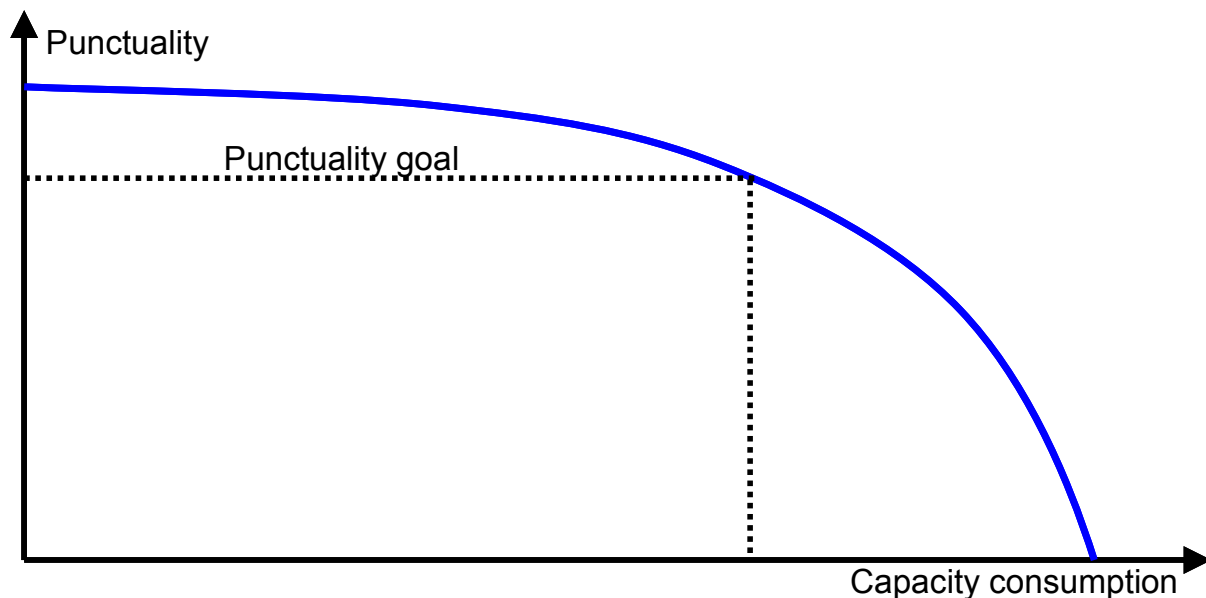


Figure 13: The coherence between punctuality and capacity consumption. Based on [5][18].

It is not only the punctuality that restricts railway capacity. Sometimes the railway capacity is reduced due to capacity restrictions outside the analysis area – so-called network effects⁶. Figure 14 is an example of network effects as it is not possible to operate more (blue unbroken) trains on the single track line because of the many (red broken) trains operated on the double track line.

⁶ For more information about network effects, please refer to [3], [4], [7] and [12]

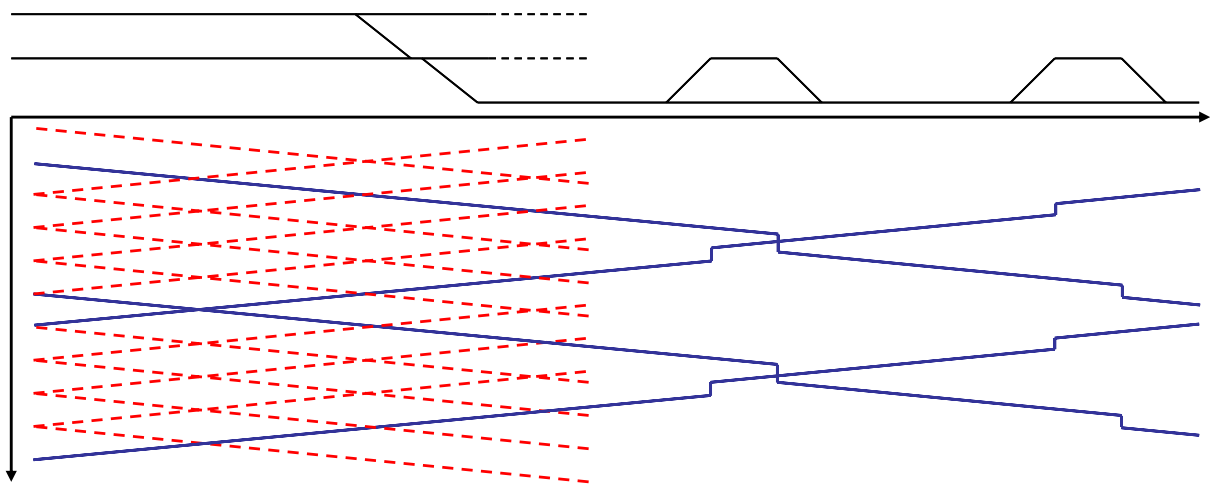


Figure 14: Limited possibility to operate more trains. Based on [8].

Network effects makes it difficult to state railway capacity for an entire railway network instead of “just” a railway line as described in this article. This is because it is not possible to evaluate the railway capacity for larger networks as the entire train graph becomes too big and complex to compress and although it would be possible to compress the timetable graph’s idle capacity might not be found.

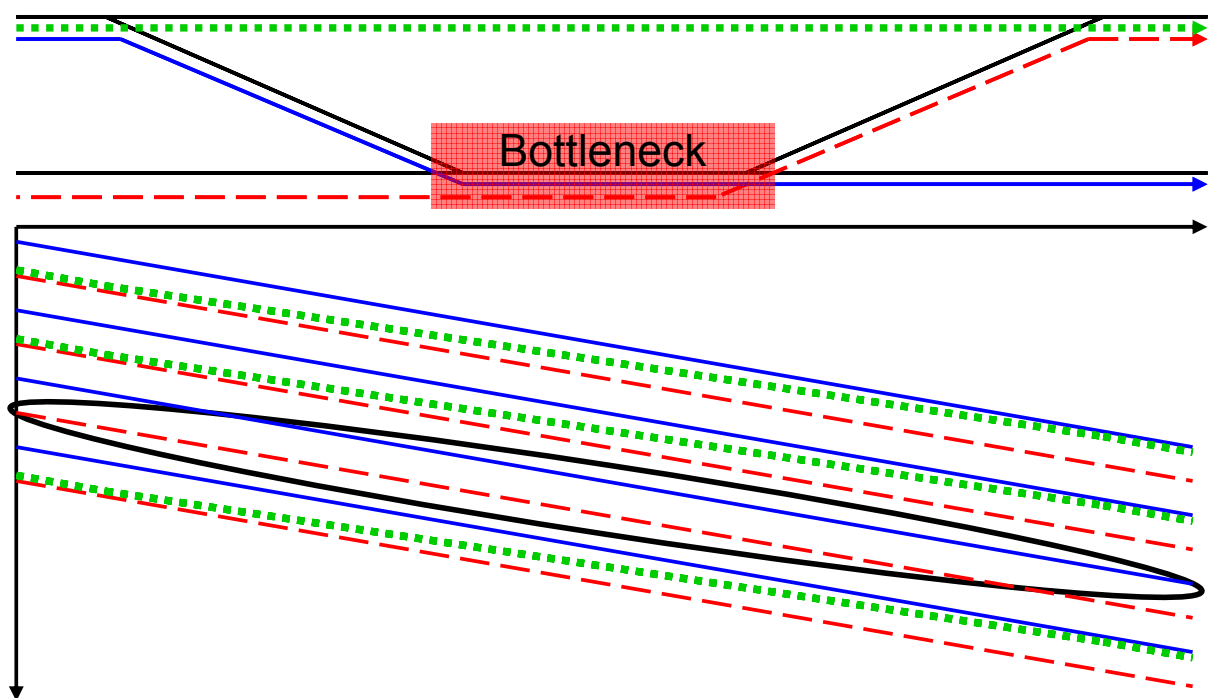


Figure 15: Timetable graph compression (for one direction) in a small network.

Figure 15 shows an example where idle capacity is not found when a timetable graph is compressed. The network has a bottleneck where the (blue unbroken) trains and the (red broken) trains share the same track. Although it is not possible to compress the timetable graphs anymore at the bottleneck it is still possible to operate more (green dotted) trains as there is a free time slot for these trains (cf. circled area in figure 15). The reason why it is still

possible to operate more (green dotted) trains is that these trains do not pass through the same bottleneck as the (blue unbroken) trains and the (red broken) trains.

Due to the difficulties in identifying idle railway capacity in networks the Austrian Railways (ÖBB) has chosen to examine idle capacity in networks using a train path searching tool (within the software tool RailSys) [21]. Using the train path searching tool it is possible to examine if it is possible to add additional trains in the railway network and thereby to identify idle capacity.

7 Conclusion

This article describes how railway capacity can be stated based on the internationally accepted UIC 406 capacity method. The article describes how to measure the capacity consumption and the capacity utilization. The capacity consumption can be measured by compressing the timetable graphs while the capacity utilization can be measured by examining the number of trains, average speed, heterogeneity and stability.

When compressing the timetable graphs to measure the capacity consumption one has to be aware that it is the maximum capacity, which is measured. Many capacity restrictions can reduce this maximum capacity. Therefore, it is not possible to have a capacity consumption that is too high why one either has to accept lower maximum value of the capacity consumption or use quality factors when stating capacity consumption.

As it is difficult to state the capacity consumption exactly in a straightforward way, it is suggested that the intervals of capacity consumption are described verbally instead of in percent intervals. This makes it possible to present maps that are more easy/straightforward to read and understand.

To have a good knowledge about the railway capacity, it is important to know both the capacity consumption and how the capacity is utilized. It is however not possible to visualize (or present) both at the same time. Therefore, it is necessary to have a GIS system visualizing e.g. the capacity consumption with the possibility to click on the line sections to examine the actual capacity utilization.

The exact line sections to work out railway capacity vary over the years. To be able to compare the capacity consumption and utilization over time it is important to have an overlap statement when changing the methodology for stating railway capacity – else it is not possible to follow the development.

Capacity statements do not take network effects of the railway system into account. This results in difficulties when identifying idle/usable capacity. This is due to network effects in the railway system and the fact that operating more trains can result in reduced punctuality.

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